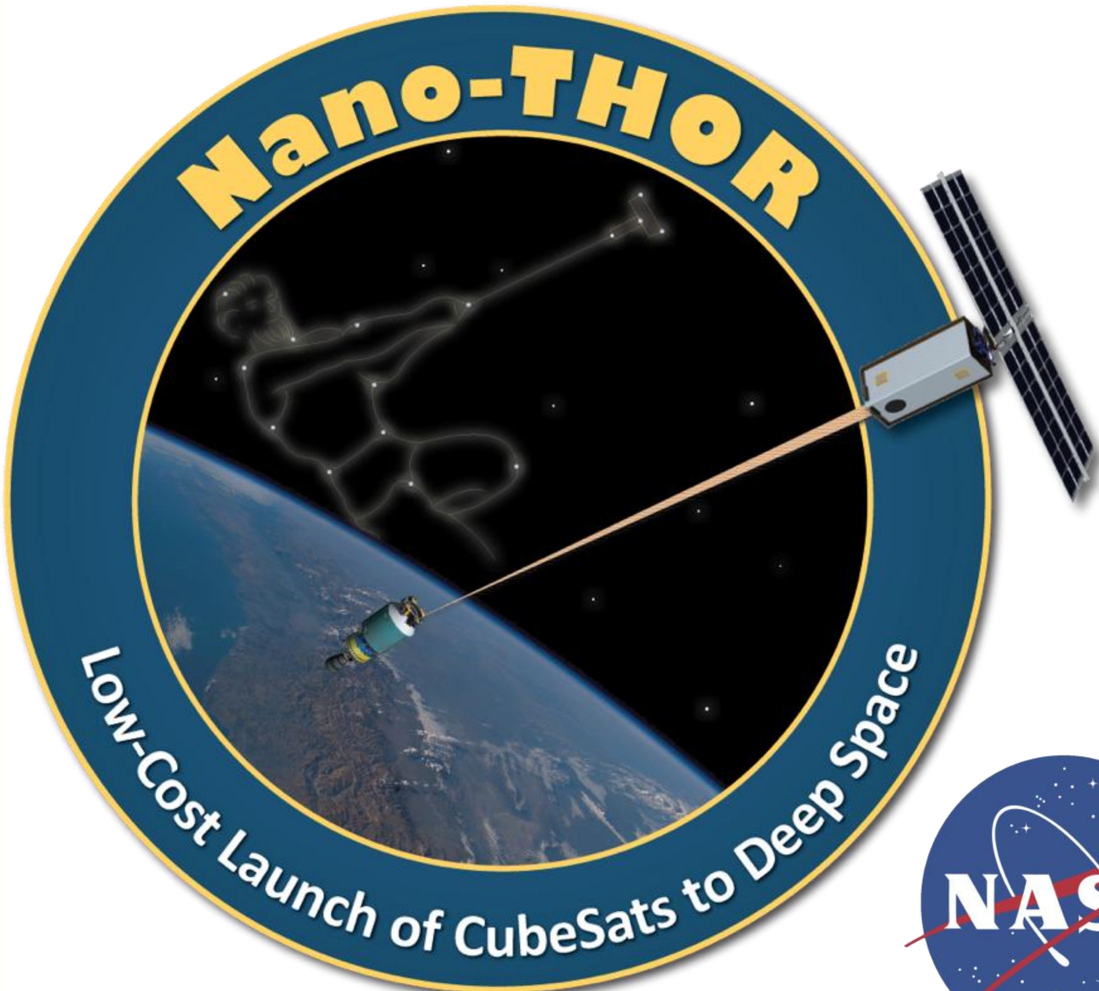
NanoTHOR

TETHERS UNLIMITED
Advanced Propulsion, Power, & Comm.
for Space, Sea, & Air

Low-Cost Launch of Nanosatellites to Deep Space



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NASA

NIAC
NASA Innovative Advanced Concepts

NanoTHOR

- **Challenge Addressed:**
  - Emerging nanosatellite and CubeSat technologies could enable NASA to perform Exploration missions at lower cost, but ride-share opportunities to Earth escape are very rare
  - Restrictions on secondary payload stored energy limit opportunities to use conventional rockets to boost nanosats

NanoTHOR Concept

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- **Proposed Solution:**
  - Launch nanosatellite as ride-share on GEO satellite launch
  - The "Nanosatellite Tethered High-Orbit Release" (NanoTHOR) system will use a simple high-strength tether to scavenge the orbital momentum and residual propellant of GEO upper stages to 'sling' multiple nanosatellites to Earth-escape
  - NanoTHOR enables *fast* (e.g. few hours or few days) transfer of multiple nanosats to escape trajectories with effective specific impulse comparable to EP thrusters that would require many months

NanoTHOR Concept

- **Benefits**
  - Enables delivery of secondary payloads to deep space trajectories without requiring chemical rockets that would pose a risk to the primary payload
  - NanoTHOR tether is re-usable, and can boost multiple nanosatellites with a lower total required mass than rocket technologies

CONOPS

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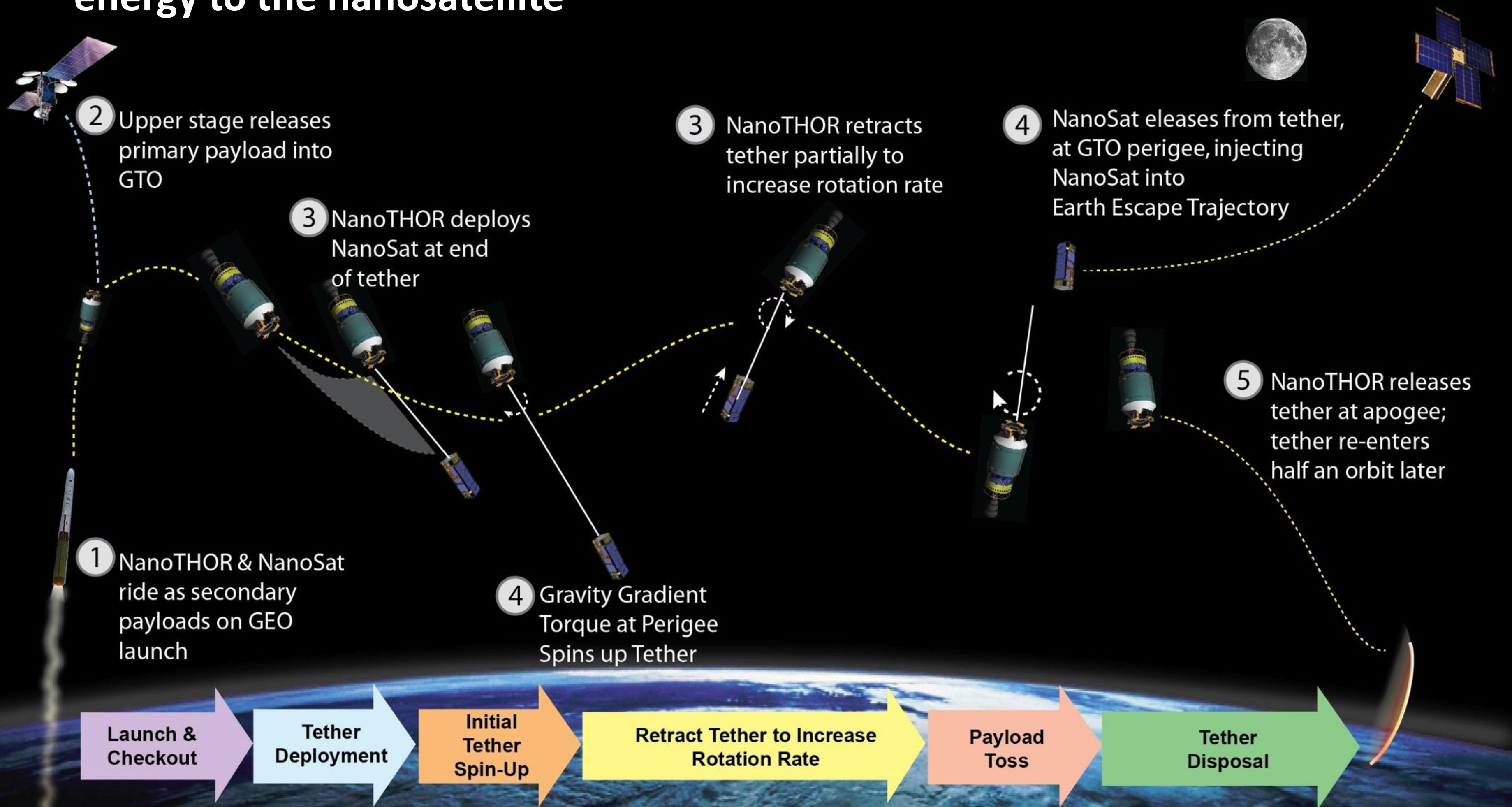
- **Nanosat & NanoTHOR ride as secondary payloads on GEO satellite launch**
- **NanoTHOR uses slender, high-strength tether to transfer stage's orbital energy to the nanosatellite**



Tether Spin-Up CONOPS

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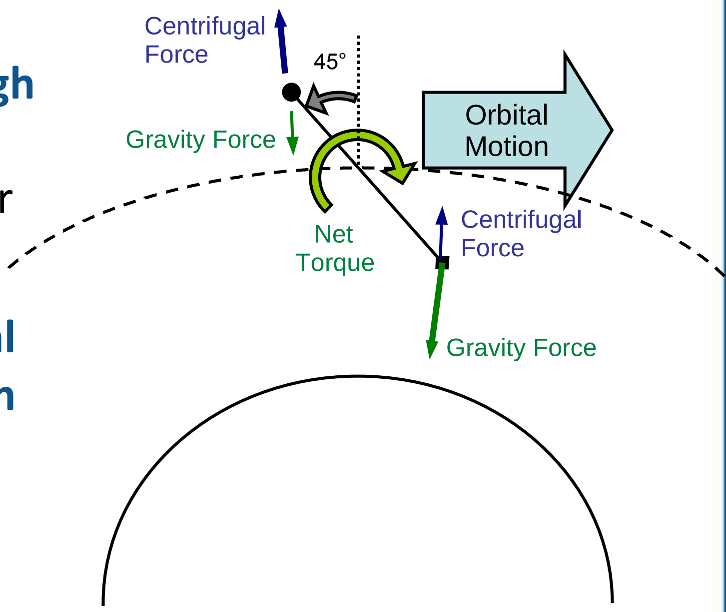
- **Getting tether deployed and 'spun up' in highly elliptical GTO orbit is a significant dynamics control challenge**
- **In elliptical orbit, the tether spin angular momentum and orbital angular momentum are coupled**
- **Tether spin gets a 'kick' every time it passes through perigee**
  - Direction of kick depends upon phasing of tether rotation w.r.t. orbit
- **Once tether is spinning fast enough to rotate several times during a perigee pass, the angular momentum exchange becomes small**
- **Proposed Solution:**
  - First, to start tether spinning:
    - Control tether deployment over several orbits to maximize transfer of orbit angular momentum to spin angular momentum
  - Once a stable spin is established:
    - Retract tether to increase spin rate (via conservation of angular momentum) until required tip velocity is reached



Tether Spin Equations of Motion

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Rate of change of tether rotation rate w.r.t. true anomaly

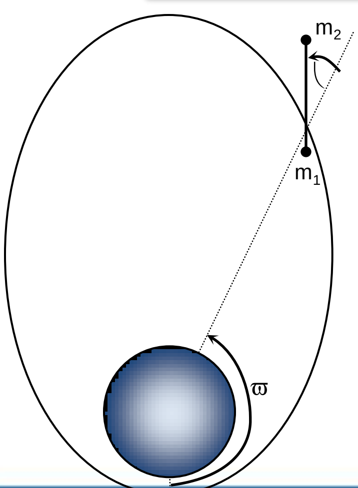
Effect of tether deployment

$$q'' = 2\left(q' + 1\right)\left[\frac{e \sin n}{1 + e \cos n} - M^* \frac{\mathsf{L}'}{\mathsf{L}}\right] - \frac{3}{1 + e \cos n} \sin q \cos q$$

$$\mathsf{L}'' = \frac{2e \sin n}{1 + e \cos n}\mathsf{L}' - M^{**}\frac{\left(\mathsf{L}'\right)^2}{\mathsf{L}} + M^{***}\mathsf{L}\left[\left(q' + 1\right)^2 + \frac{3\cos^2 q - 1}{1 + e \cos n}\right] - T^*$$

Rate of change of tether deployment rate w.r.t. true anomaly

Normalized tether tension



$\left(\ \right)¢ = \dfrac{d\left(\ \right)}{dn}$

$n =$ true anomaly

$e =$ eccentricity

$q =$ in-plane libration angle

$\mathsf{L} = \dfrac{\ell}{L} =$ normalized tether length

$\ell =$ deployed tether length

$L =$ total tether length

$$T^* = \frac{T}{m_1 \dot{n}^2 L\left(m_2 + m_t\right) / \left(m_1 + m_2 + m_t\right)} = \text{ normalized tether tension}$$

$$\mathrm{M}^* = m_1\left(m_2 + \frac{m_t}{2}\right) \Big/ \left[m^* m\right]$$

$$\mathrm{M}^{**} = \left(2m_1 - m\right)\frac{m_t}{2} \Big/ \left[m_1\left(m_2 + m_t\right)\right]$$

$$\mathrm{M}^{***} = \left(m_2 + \frac{m_t}{2}\right) \Big/ \left(m_2 + m_t\right)$$

$$m = m_1 + m_2 + m_t$$

$$m^* = \frac{\left(m_1 + \frac{m_t}{2}\right)\left(m_2 + \frac{m_t}{2}\right)}{m} - \frac{m_t}{6} = \text{reduced mass of system}$$

Spin Equation Analysis

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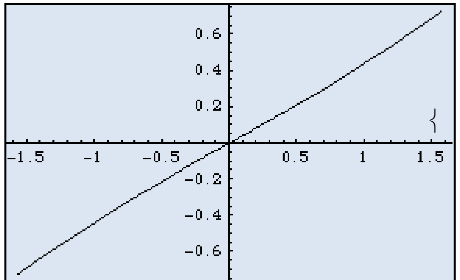
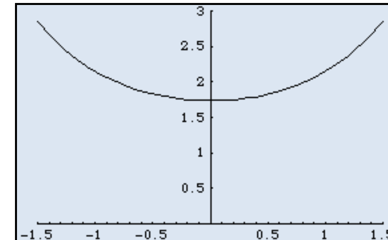
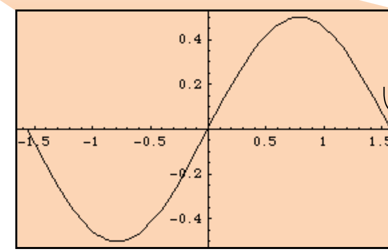
- Tether deployment always slows rotation
- Tether retraction increases rotation rate





$$\theta'' = 2(\theta' + 1)\left[\frac{e \sin \nu}{1 + e \cos \nu} - M^{*}\frac{\Lambda'}{\Lambda}\right] - \frac{3}{1 + e \cos \nu}\sin\theta\cos\theta$$

No dependence on θ and symmetric about periapse, so contribution minimal



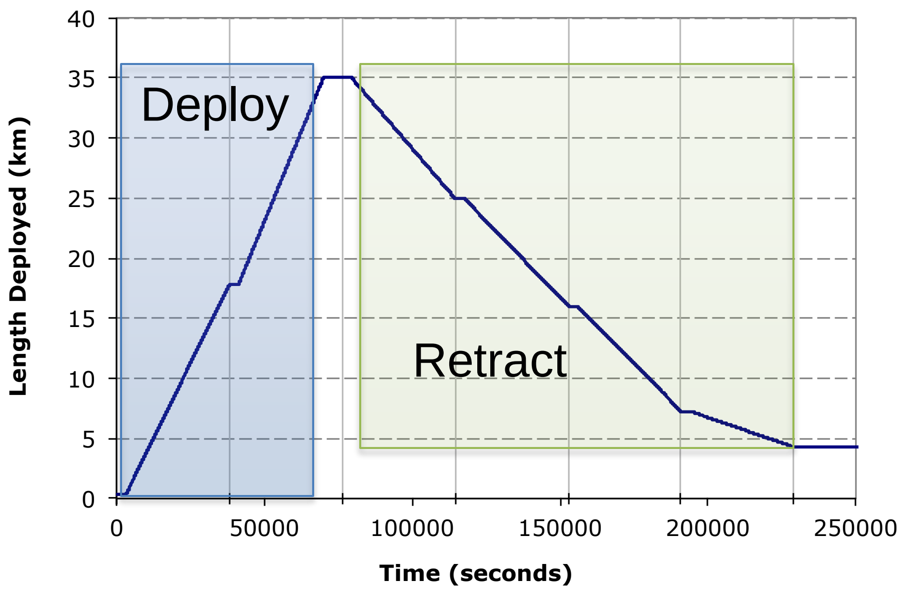
We want θ to be ≈ -30° to maximize spin-up of tether during perigee pass

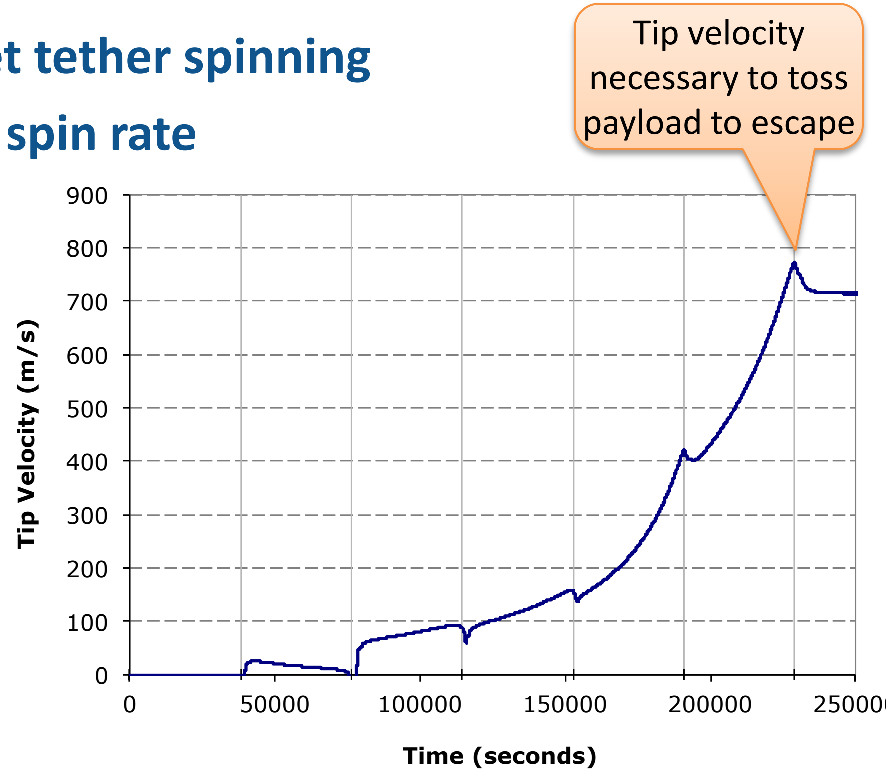
<u>Solution:</u> Control tether deployment rate so that tether passes perigee with ~ -30° in-plane libration angle while keeping tension always > 0

e.g. keep: $\Lambda'' < \frac{2e \sin \nu}{1 + e \cos \nu}\Lambda' - M^{**}\frac{(\Lambda')^2}{\Lambda} + M^{***}\Lambda\left[(\theta' + 1)^2 + \frac{3\cos^2\theta - 1}{1 + e \cos \nu}\right]$

Tether Spin-Up in GTO

- Deploy tether over 2 orbits at ~50 cm/s
- Vary deployment rate so that tether is ~30° behind vertical when approaching perigee
- Gravity gradient provides torque to get tether spinning
- Retract tether at ~25 cm/s to increase spin rate





We can use tether reeling in the Earth's gravity well to spin up the tether

Tether Design & Mass

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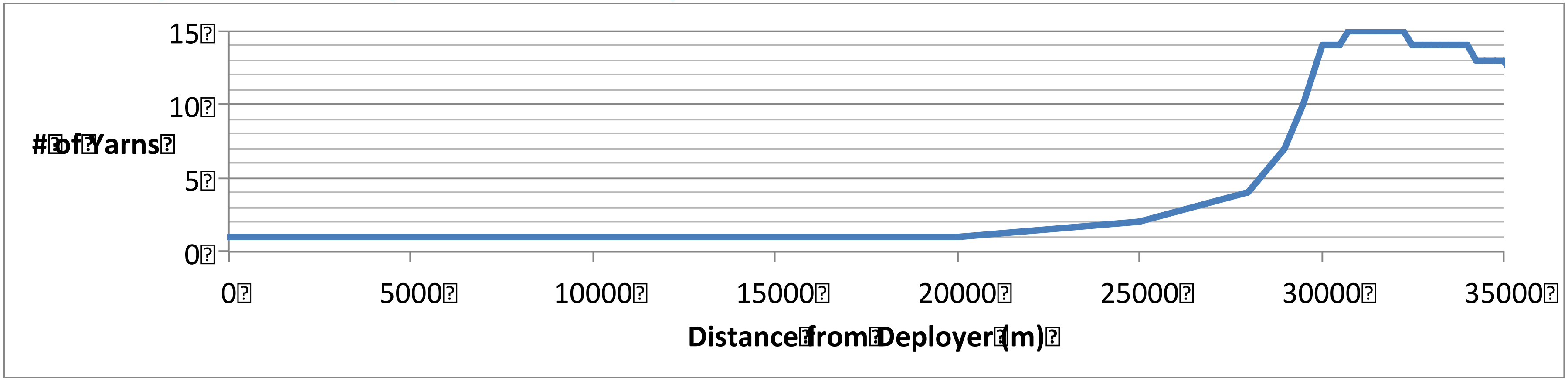
- **Material: Dyneema/Spectra (HMWPE)**
- **Braided tape of 88-Tex yarns (think dental floss)**
- **Stepwise-tapered to optimize mass**



- **Total tether mass: 12 kg ← for a 10 kg payload**
- **Tether mass is > solid propellant mass to provide the same ΔV, but tether is re-usable for multiple payloads**

Orbital Winch™

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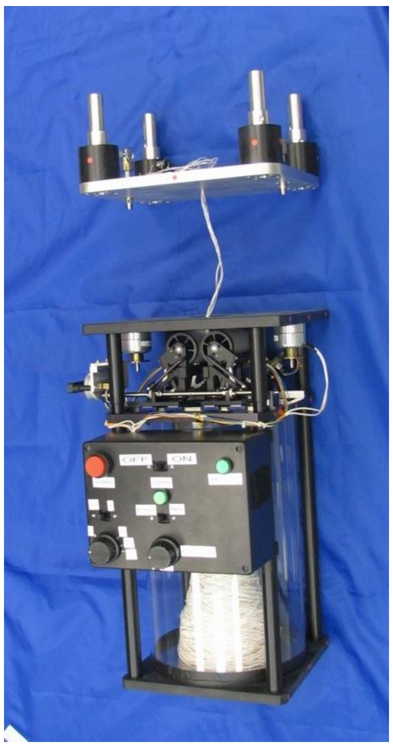
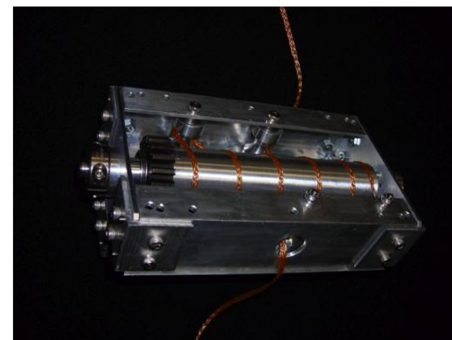
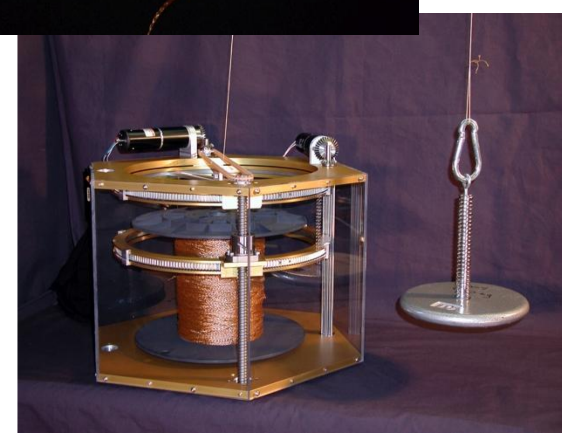
- **NanoTHOR leverages tether deployment/retraction mechanism technology developed under NASA and DARPA funding**
  - Deployer component matured to TRL-5 by microgravity testing
  - High-load retraction capability demonstrated to TRL-4







Summary

- **Primary objective is to enable frequent and low-cost delivery of nanosats to Earth escape trajectories**
- **Secondary objective is to develop the "smallest, simplest" useful momentum-exchange tether to enable affordable maturation of tether propulsion**
- **NanoTHOR "harvests" orbital energy from spent upper stage to boost nanosat payloads**
- **Control of tether deployment and retraction can enable ΔV's sufficient for GTO->Escape boost**
  - Boosting multiple nanosats per mission is feasible
- **Leverage recent multi-$M investments by NASA & DoD in tether tech maturation to enable near-term validation**
- **Coordination with launch provider needed to enable operations**